

# Reactor Neutrino Measurement of $\bar{\nu}_{13}$

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# Neutrino Oscillation Parameters

## Beamstop Neutrinos

$\bar{\nu}_e$   $\bar{\nu}_\mu$   $\bar{\nu}_s$   $\bar{\nu}_\tau$   $\bar{\nu}_e$



## Atmospheric, Reactor, Accelerator Neutrinos

$\bar{\nu}_e$   $\bar{\nu}_\mu$   $\bar{\nu}_\tau$

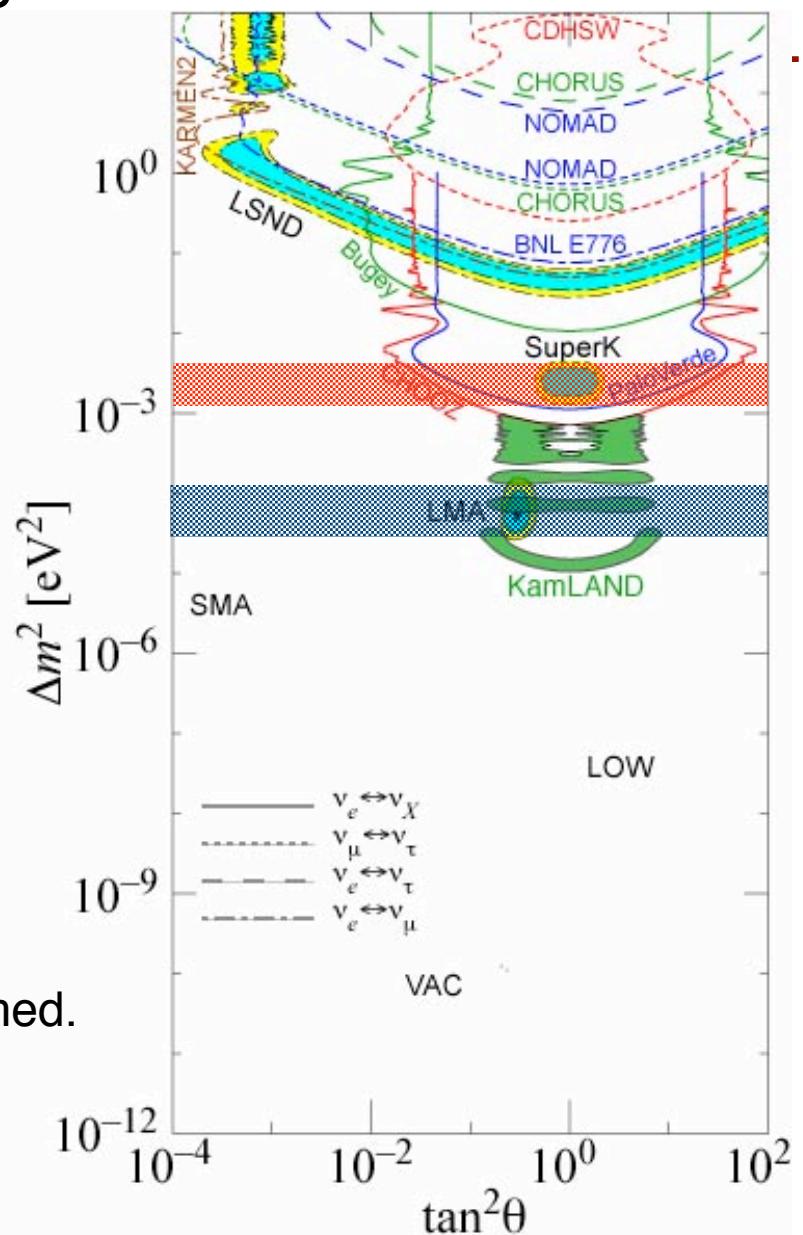


## Solar and Reactor Neutrinos

$\bar{\nu}_e$   $\bar{\nu}_\mu$   $\bar{\nu}_{\tau,\mu}$



Except for LSND,  $\Delta m_{ij}^2$  measured *and* confirmed.



# $\theta_{13}$ and CP Violation

## $U_{\text{MNSP}}$ Neutrino Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

*Dirac phase*

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{i\theta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ e^{i\theta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ \sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & e^{i\theta/2} \\ 0 & e^{i\theta/2+i\alpha} & 0 \end{pmatrix}$$

*Majorana phases*

atmospheric, K2K

$$\theta_{23} = \sim 45^\circ$$

*maximal*

reactor and accelerator

$$\tan^2 \theta_{13} < 0.03 \text{ at 90% CL}$$

*small ... at best*

SNO, solar SK, KamLAND

$$\theta_{12} \sim 30^\circ$$

*large*

No good ‘ad hoc’ model to predict  $\theta_{13}$ .  
If  $\theta_{13} < 10^{-3} \theta_{12}$ , perhaps a symmetry?

$\theta_{13}$  yet to be measured  
determines accessibility to CP phase

# Why Are Neutrino Oscillation Measurements Important?

## Physics at high mass scales, physics of flavor, and unification:

- Why are neutrino masses so small?
- Why are the mixing angles *large, maximal, and small?*
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

□<sub>13</sub>

$$U_{MNSP} =$$

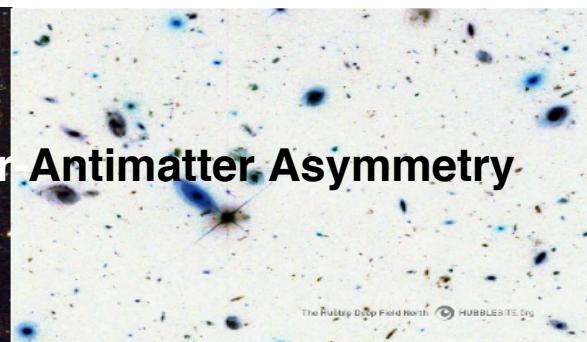
big	big	small?
big	big	big
big	big	big



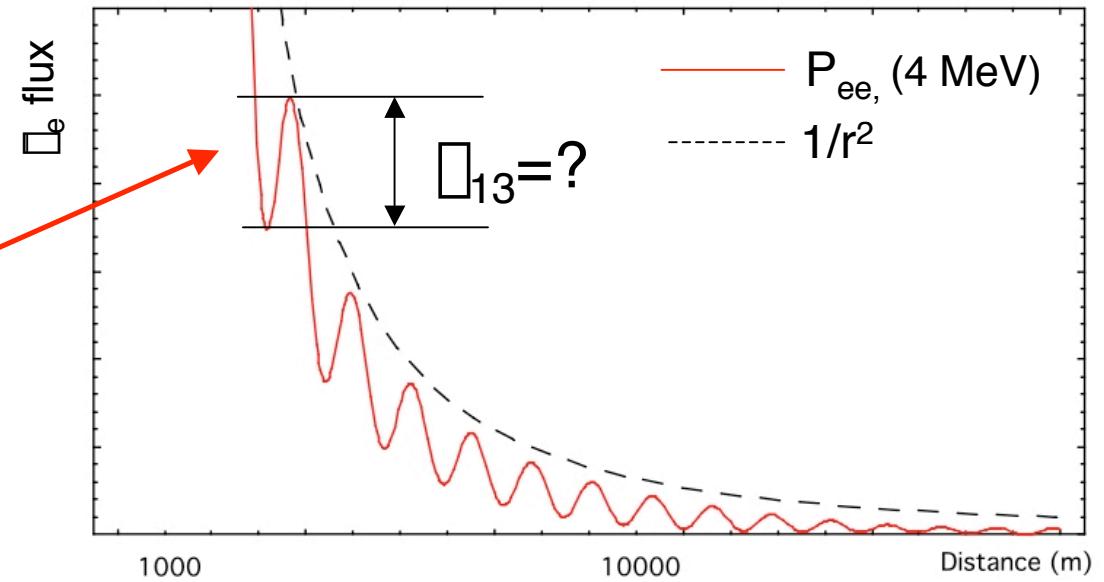
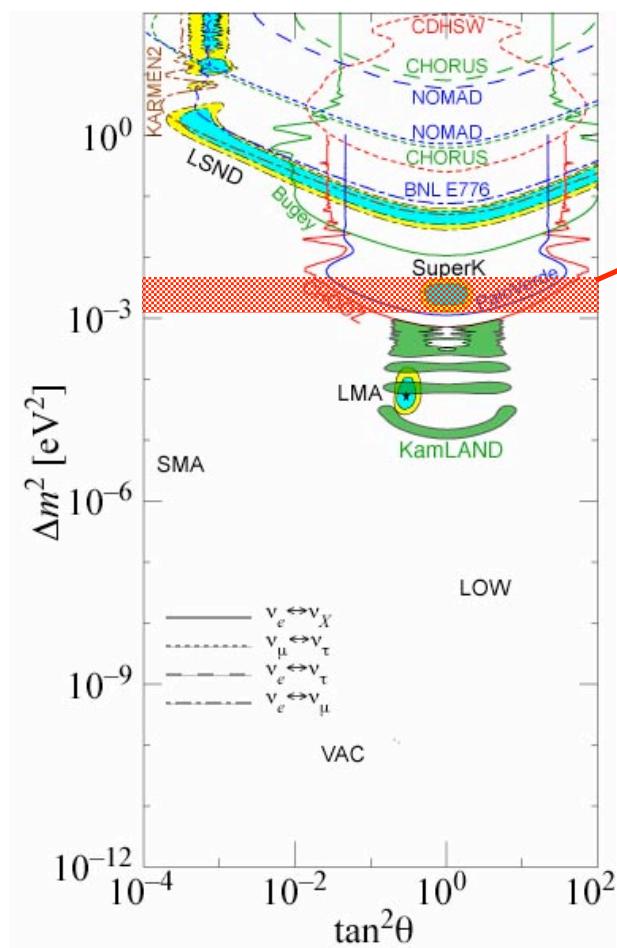
$$V_{CKM} =$$

big	small	tiny
small	big	tiny
tiny	tiny	big

- Understanding the role of neutrinos in the early Universe



# Reactor Neutrino Measurement of $\Delta m_{13}^2$ - Basic Idea

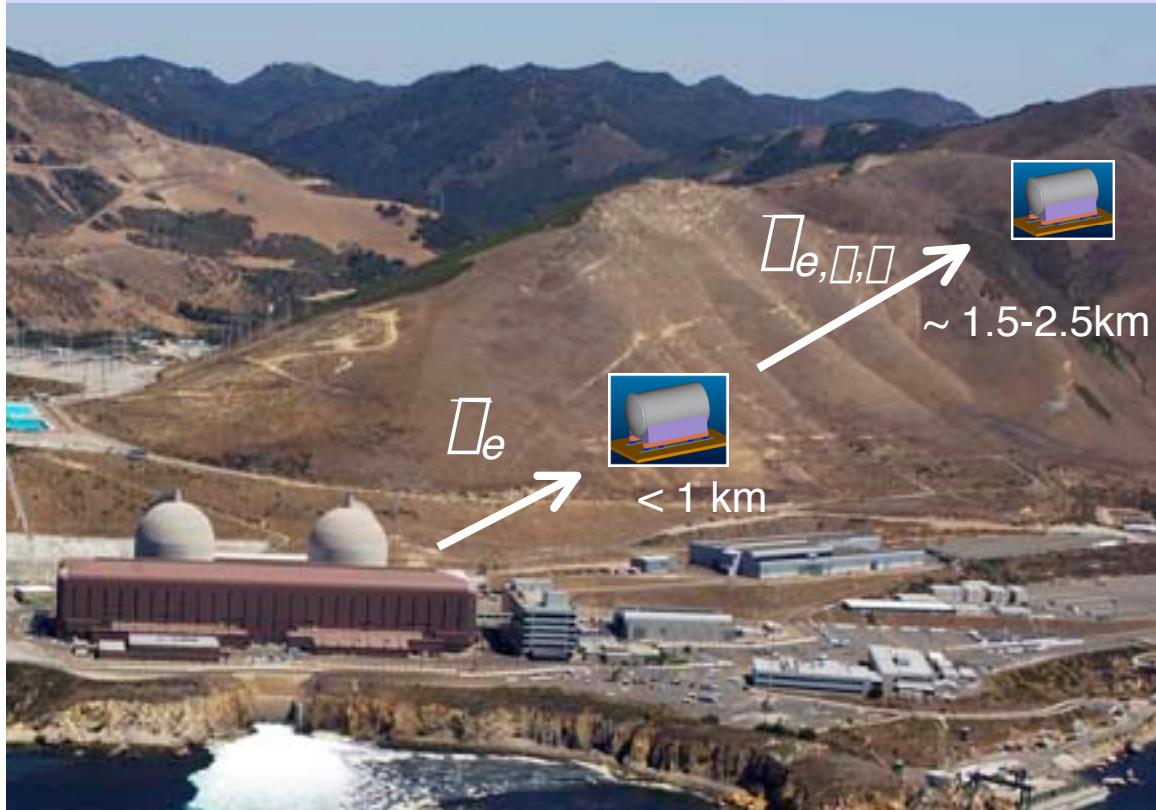


$$P_{ee} \propto 1 \propto \sin^2 2\Delta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \frac{\Delta m_{21}^2 L}{4E_\nu} \cos^4 \Delta_{13} \sin^2 2\Delta_{12}$$

atmospheric frequency dominant

last term negligible for  $\frac{\Delta m_{31}^2 L}{4E_\nu} \sim \pi/2$  and  $\sin^2 2\Delta_{13} \geq 10^{13}$

# Concept of a Reactor Neutrino Measurement of $\Delta_{13}$



scintillator  $D_e$  detectors



coincidence signal

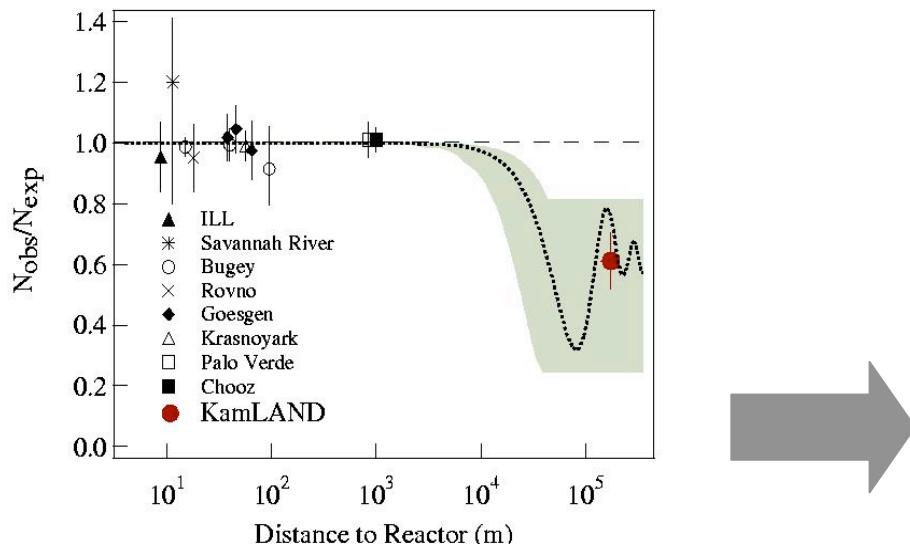
**prompt**       $e^+$  annihilation  
**delayed**       $n$  capture (in  $\mu\text{s}$ )

$$P_{ee} = 1 - \sin^2 2\Delta_{13} \sin^2 \frac{m_{31}^2 L}{4E_\nu} + \left| \frac{m_{21}^2 L}{4E_\nu} \right|^2 \cos^4 \Delta_{13} \sin^2 2\Delta_{23}$$

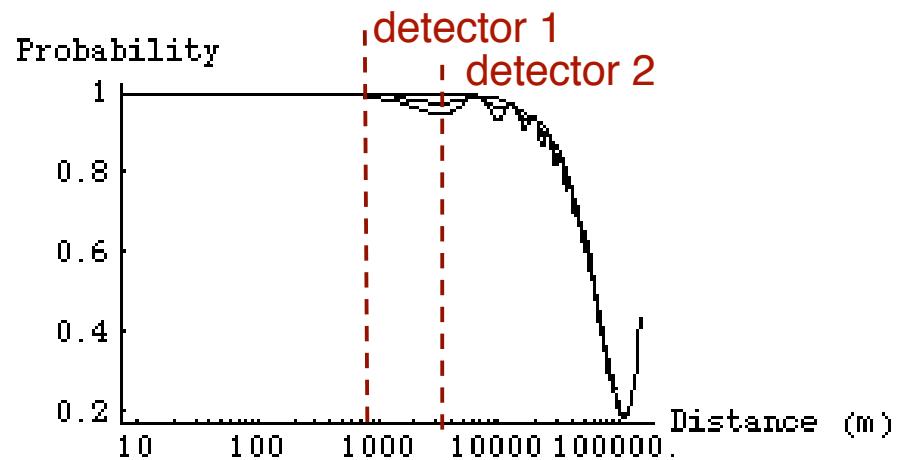
- disappearance experiment
- look for rate deviations from  $1/r^2$  and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline  $O(1 \text{ km})$ , no matter effects

# Reactor Neutrino Measurement of $\bar{\nu}_{13}$

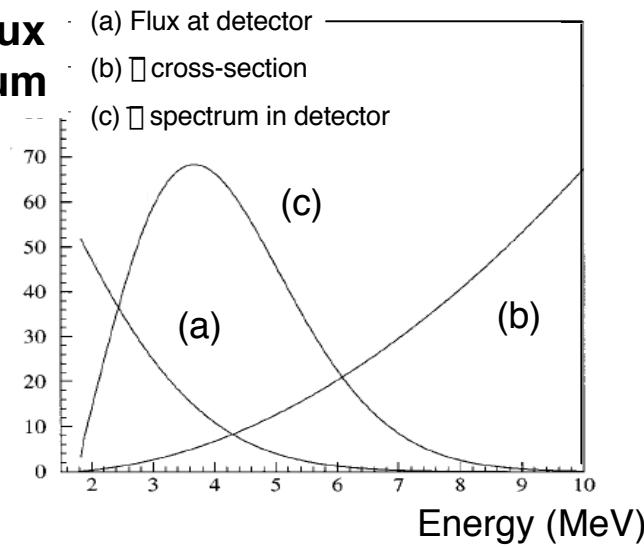
## Present Reactor Experiments



## Future $\bar{\nu}_{13}$ Reactor Experiment

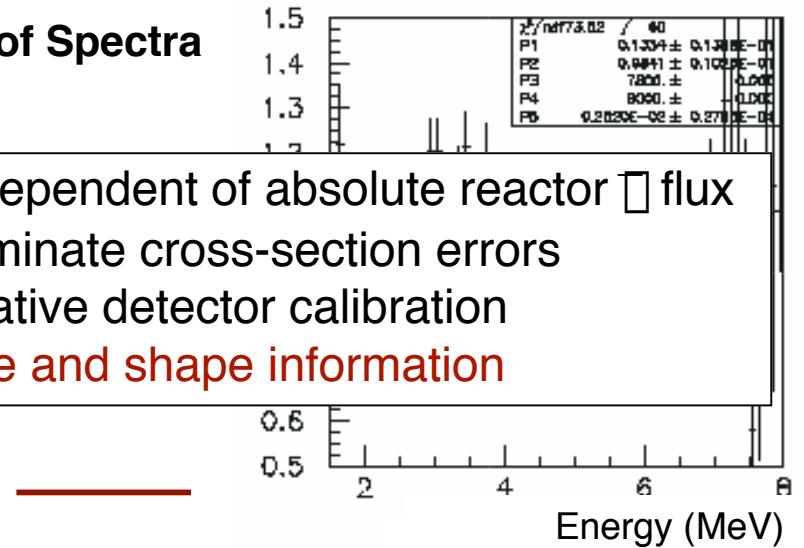


## Absolute Flux and Spectrum



## Ratio of Spectra

- independent of absolute reactor  $\bar{\nu}$  flux
- eliminate cross-section errors
- relative detector calibration
- rate and shape information

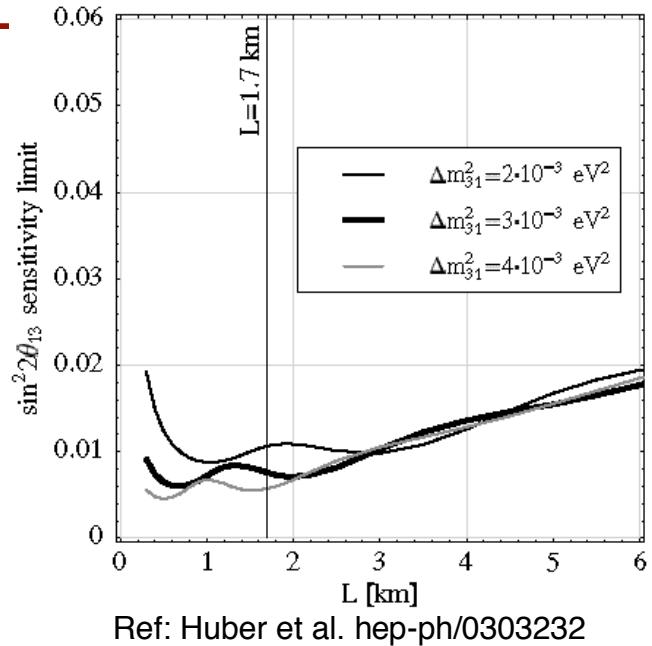


# Baseline Optimization for Detector Placement

## I. Undistorted vs Distorted Spectrum

*Optimize FAR detector with respect to NEAR*

**NEAR - FAR**      0.1 km (fixed)    1.7 km



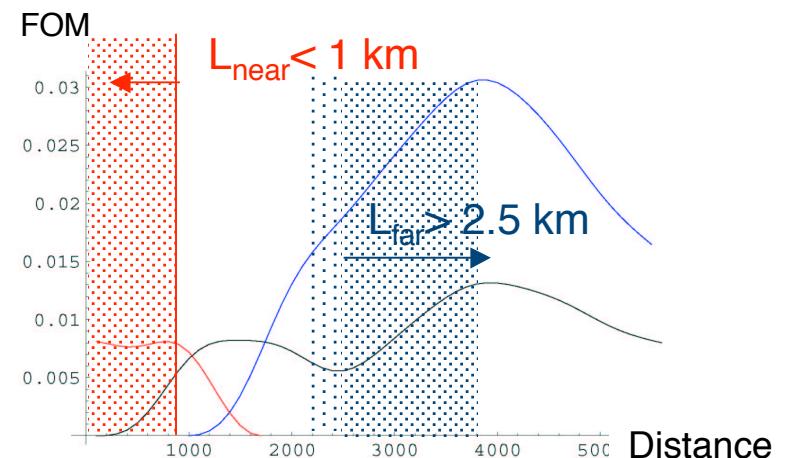
Ref: Huber et al. hep-ph/0303232

## II. Maximize Relative Distortions of Spectra

*Optimize both detector locations*

**FAR - FAR**      1 km       $\sim 2.5$ - $3$  km

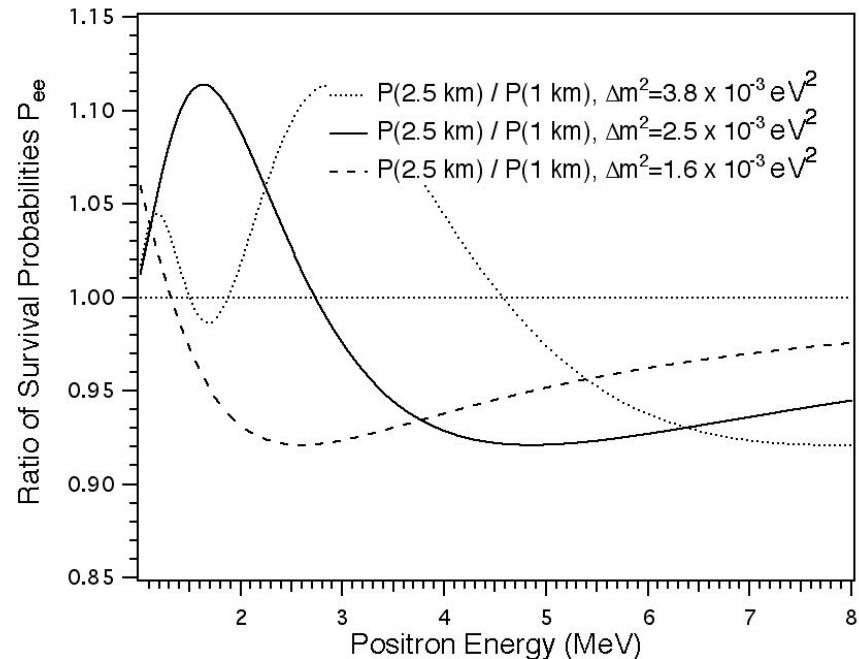
*Based on shape analysis only*



# Baseline Sensitivity to $\Delta m_{\text{atm}}^2$

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- Detector baselines sensitive to  $\Delta m_{\text{atm}}^2$ .
- Need option to adjust baseline once we have precision measurement  $\Delta m_{\text{atm}}^2$ .
- Region of interest for current  $\Delta m_{\text{atm}}^2$  region:  $L_{\text{far}} \approx 1.5 - 3 \text{ km}$ .
- Optimize baseline to see oscillation signature in ratio of spectra.

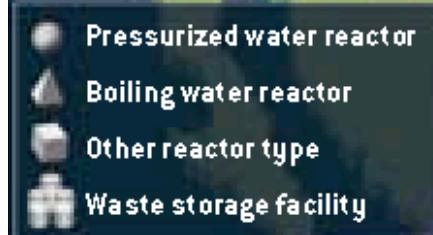


# A $\Delta_{13}$ Reactor Experiment in the US ?

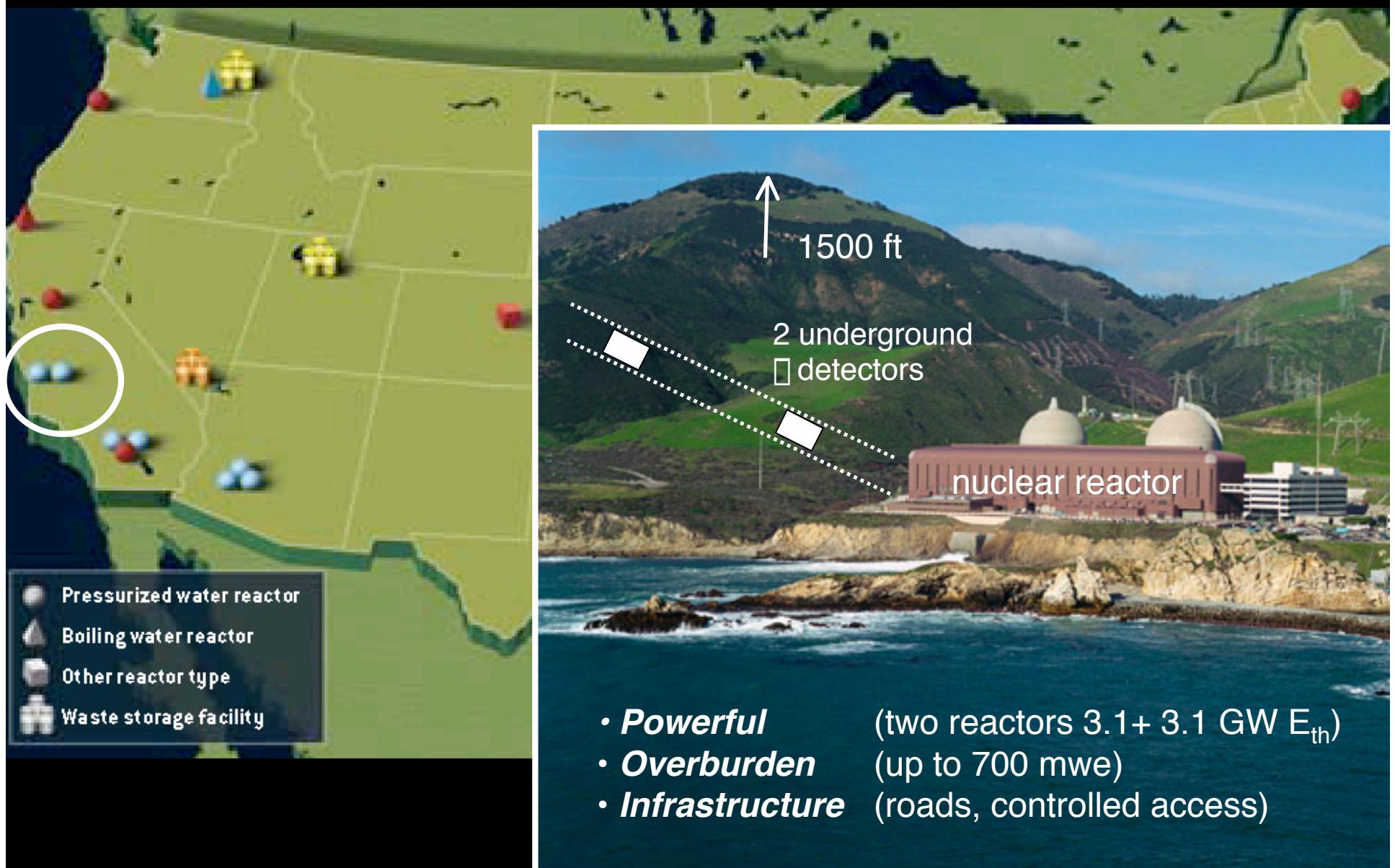
## Site Criteria

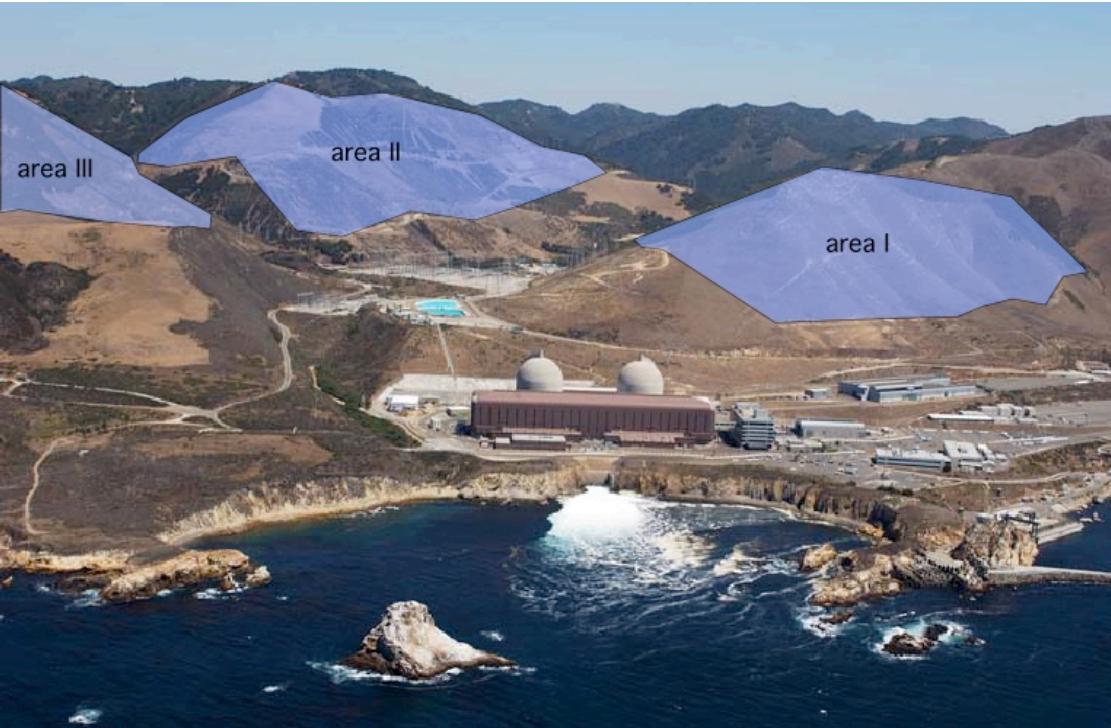
- powerful reactor
- overburden ( $> 300 \text{ mwe}$ )
- underground tunnels or detector halls
- controlled access to site

- Variable/flexible baseline for *optimization to  $\Delta m^2_{atm}$  and to demonstrate subdominant oscillation effect*
- Optimization of experiment specific to site. Site selection critical



# Diablo Canyon - An Ideal Site?



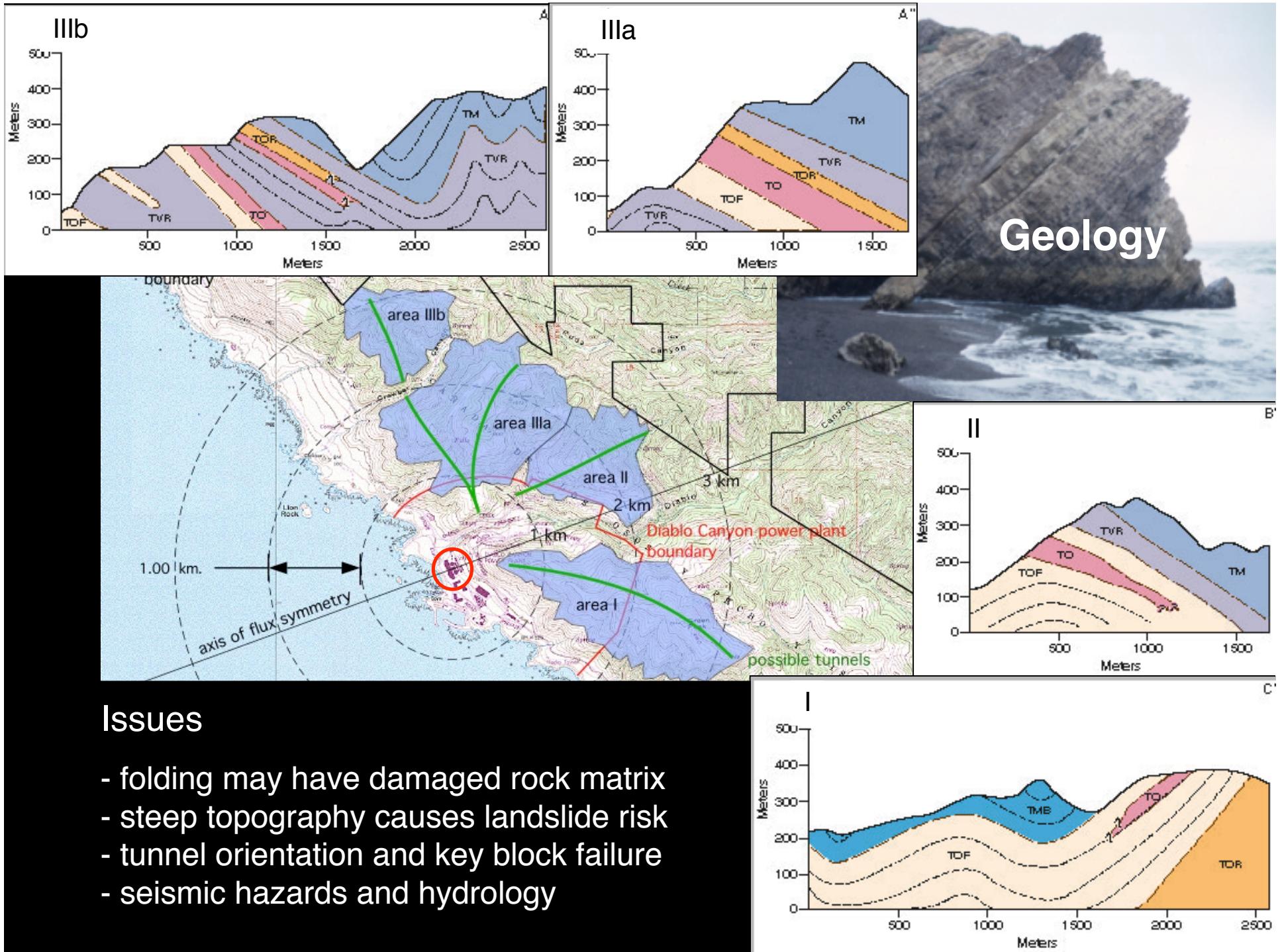


## Diablo Canyon

An Oscillation Experiment  
with Variable Baseline?

2 or 3 detectors in 1 km tunnel  
tunnel excavation required

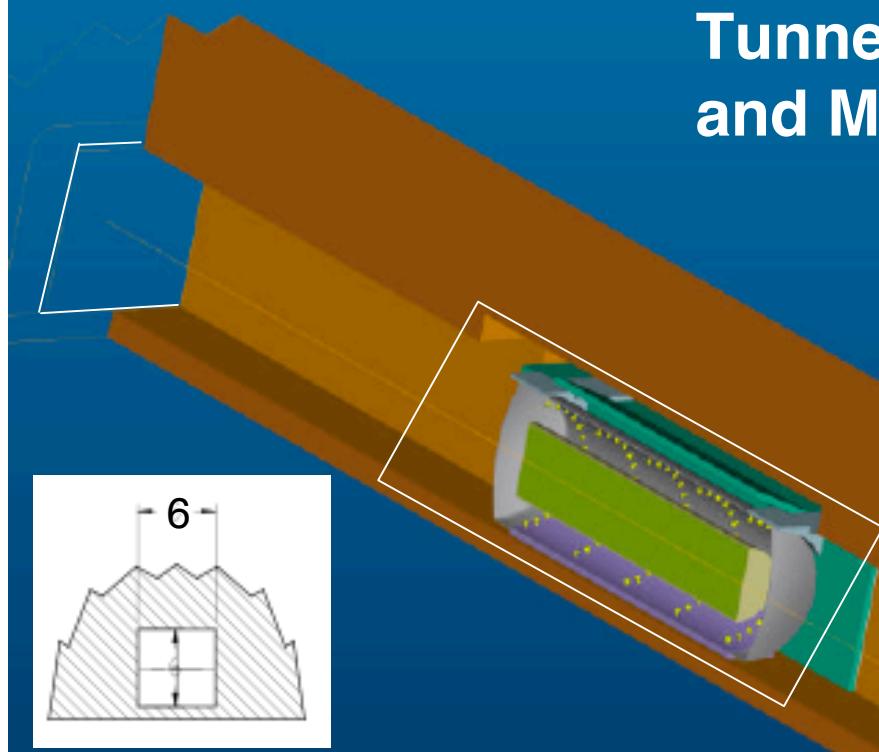




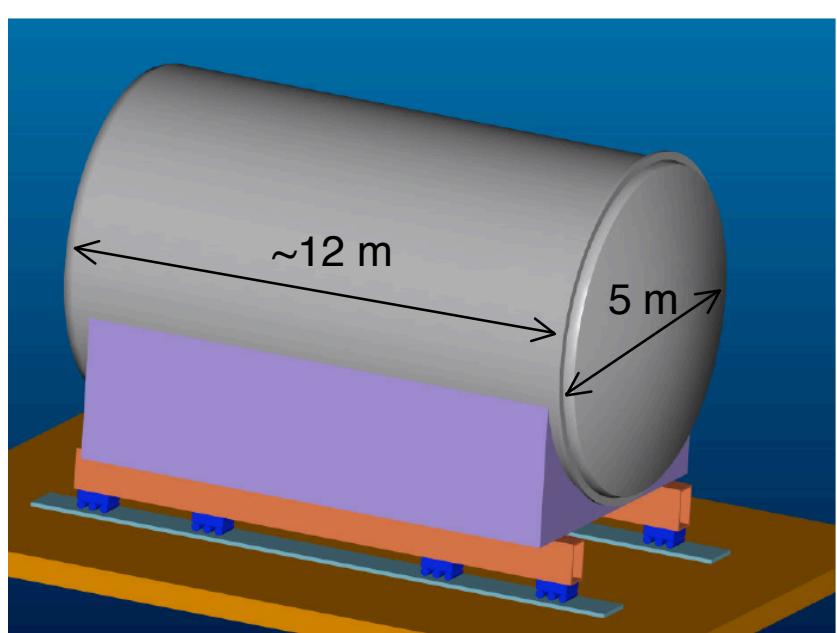
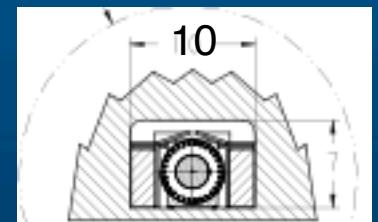
## Issues

- folding may have damaged rock matrix
- steep topography causes landslide risk
- tunnel orientation and key block failure
- seismic hazards and hydrology

# Tunnel with Multiple Detector Rooms and Movable Detectors

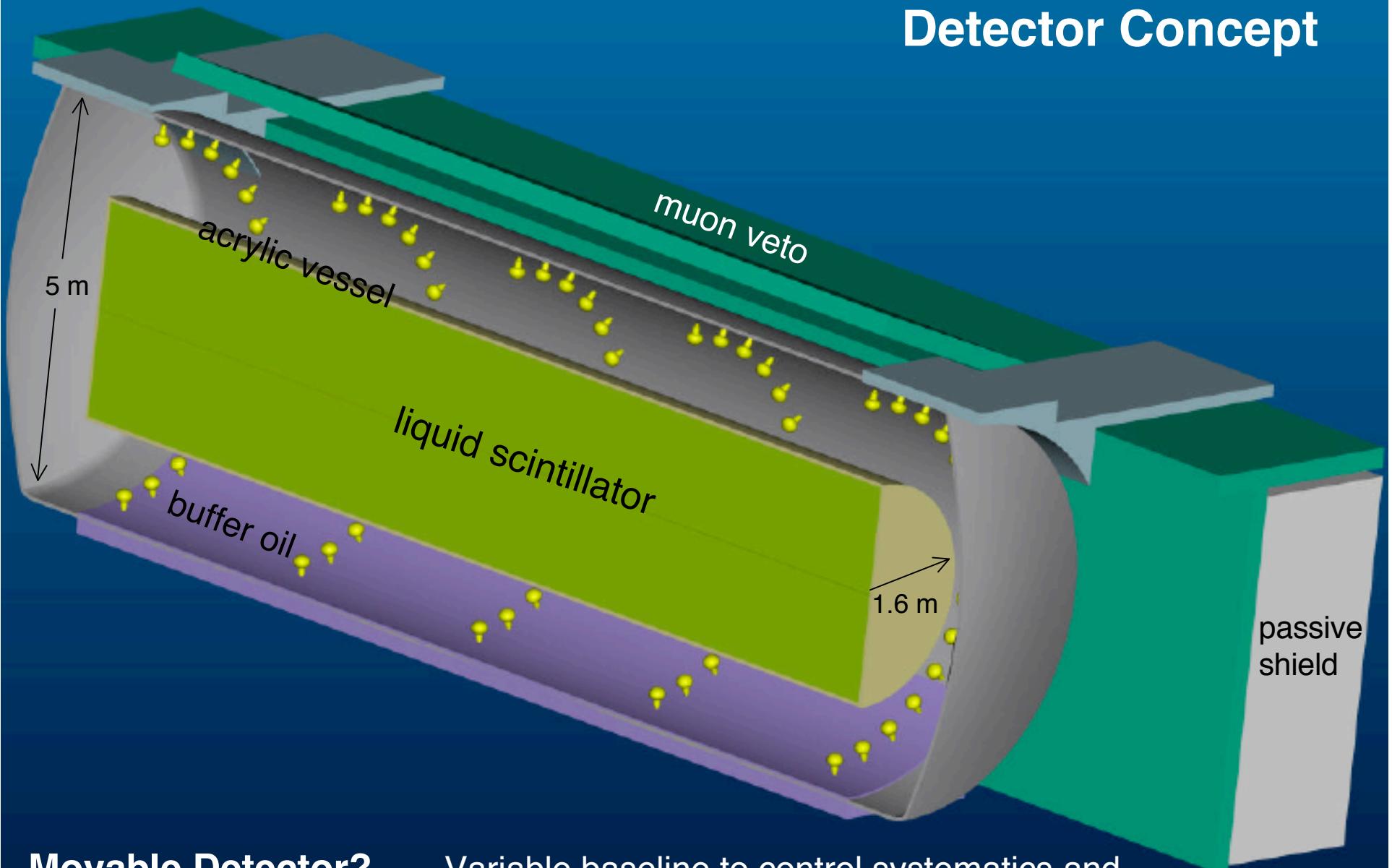


1-2 km



- Modular, movable detectors
- Volume scalable
- $V_{\text{fiducial}} \sim 50-100 \text{ t/detector}$

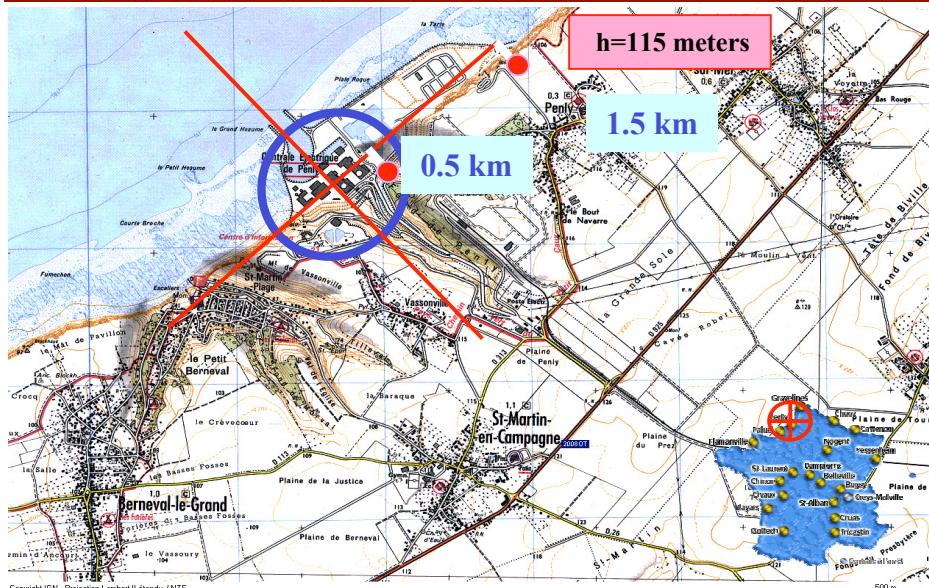
# Detector Concept



Movable Detector?

Variable baseline to control systematics and demonstrate oscillation effect (if  $\Delta_{13}$  found to be  $> 0$ )

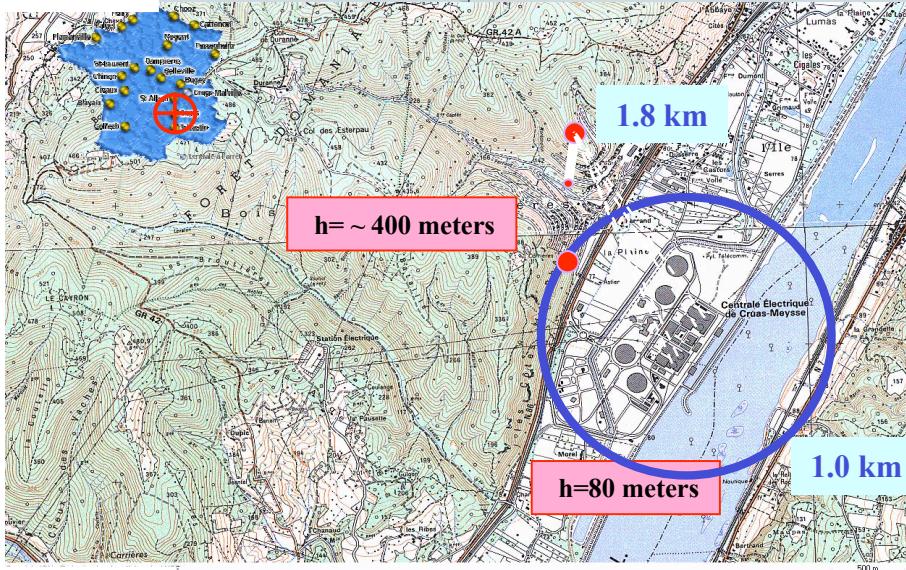
# Sites in France



## Penly

- In Haute-normandie (north coast)

Type	PWR
Cores	2
Power	8.3 GW <sub>th</sub>
Operator	EDF
Distances (km)	0.4 / 1.5
Overburden (mwe)	200 / 200
Volume @ Penly	20 t

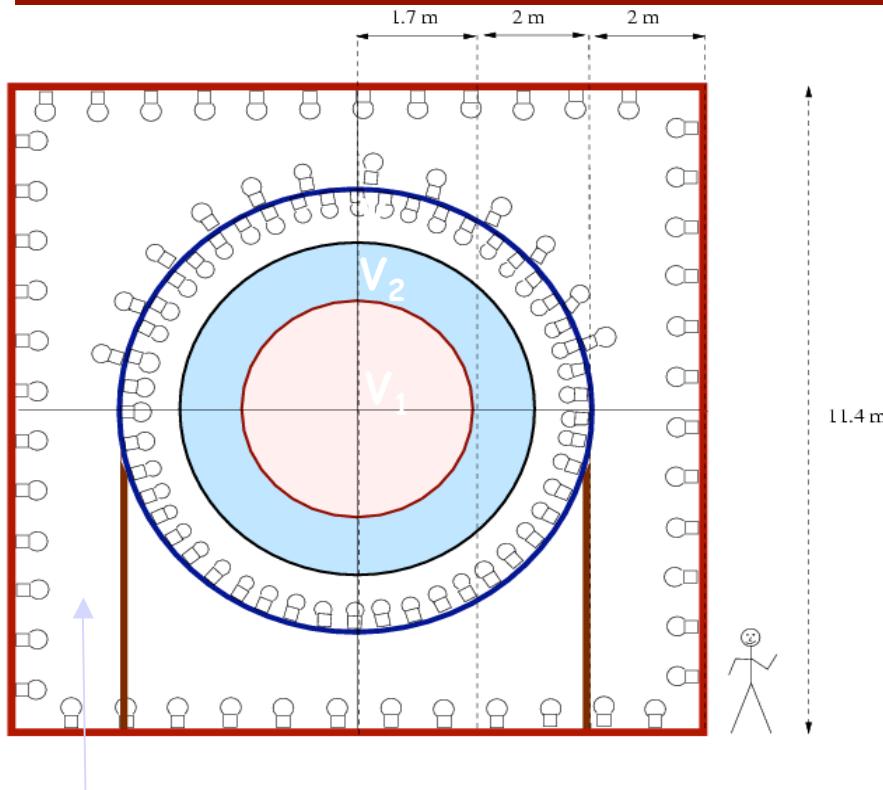


## Cruas

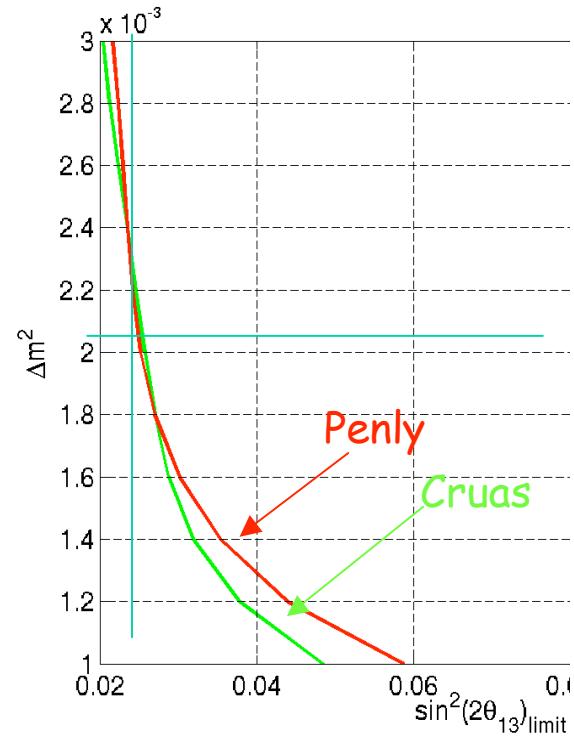
- In Ardèche (close to the Rhône)

Type	PWR
Cores	4
Power	11.8 GW <sub>th</sub>
Operator	EDF
Distances (km)	1 / 1.8
Overburden (mwe)	150 / 500
Volume @ Cruas	20 t

# Momentum in France



- Muon Veto
- $V_1$  : Gd loaded scintillator
- $V_2$  : Unloaded scintillator
- $V_3$ : Non-scintillating Buffer



$\Delta m^2 = 2.1 \times 10^{-3}$  eV $^2$   
 $\sin^2 2\theta_{13} < 0.025$  (90% C.L.)  
20 t, 3 years

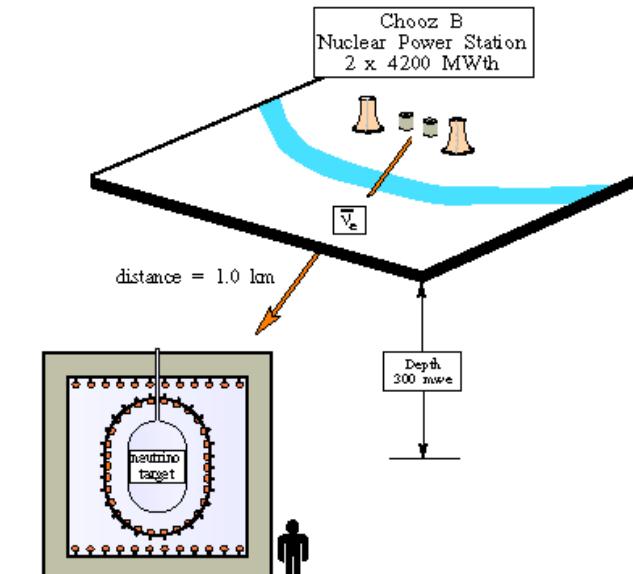
**Laboratories involved:** PCC, Collège de France & CEA/Saclay

**Activities:** site evaluations, phenomenology, Detector simulation ...

# Experimental Systematics

Best experiment to date: CHOOZ

parameter	relative error (%)
reaction cross section	1.9%
<i>relative fiducial vol.</i>	~ 0.3%
<i>rel</i> detection efficiency	≤ 1%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%



Ref: Apollonio et al., hep-ex/0301017

## Reactor Flux

- near/far ratio, choice of detector location

$$\square_{\text{flux}} < 0.2\%$$

## Detector Efficiency

- built near and far detector of same design
- calibrate *relative* detector efficiency
- variable baseline may be necessary

$$\square_{\text{rel eff}} \leq 1\%$$

## Target Volume &

## Backgrounds

- no fiducial volume cut

$$\square_{\text{target}} \sim 0.3\%$$

- external active and passive shielding for correlated backgrounds

$$\square_{\text{acc}} < 0.5\%$$

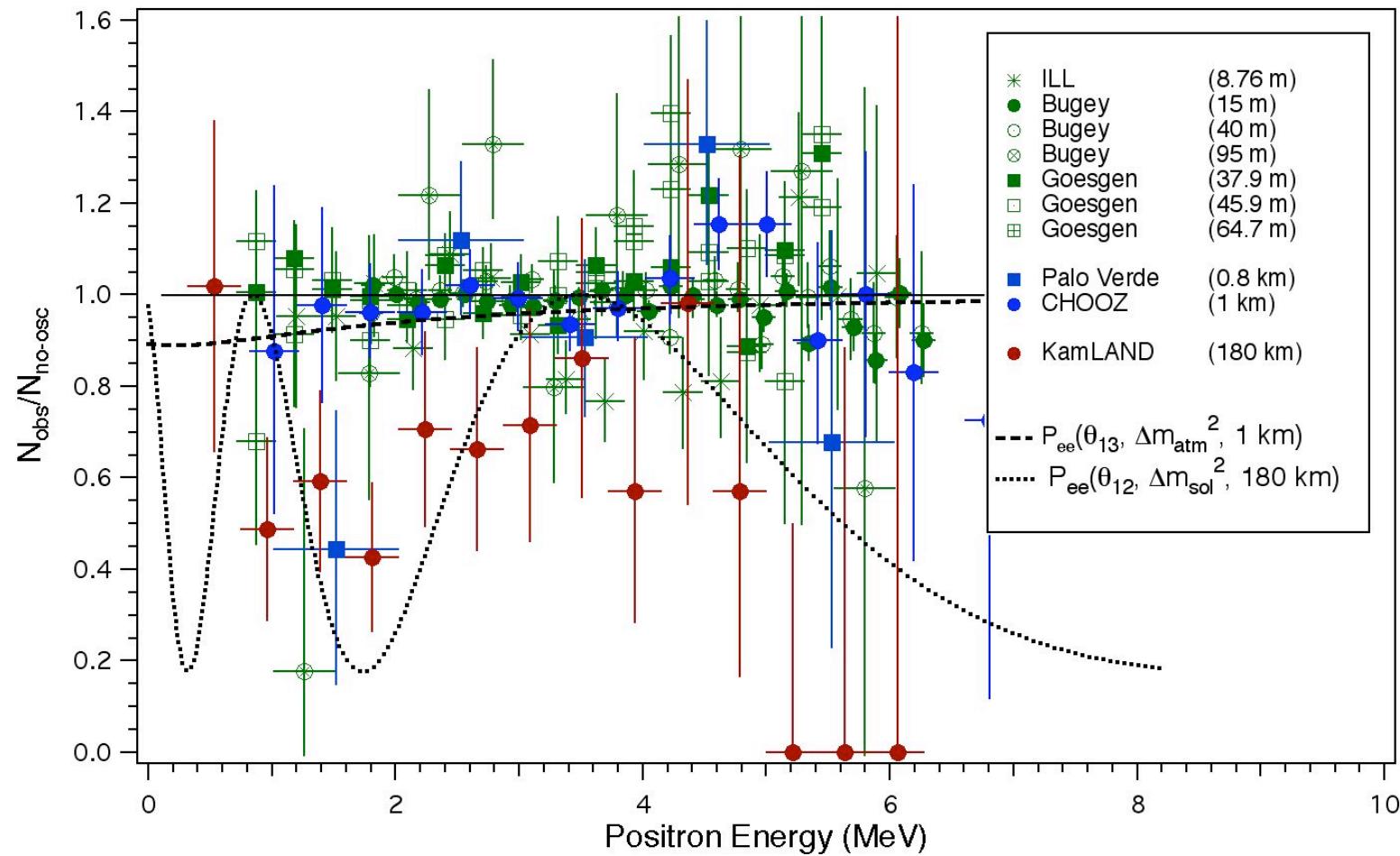
$$\square_{n \text{ bkgd}} < 1\%$$

Note: list not comprehensive

Total  $\square_{\text{syst}} \sim 1-1.5\%$

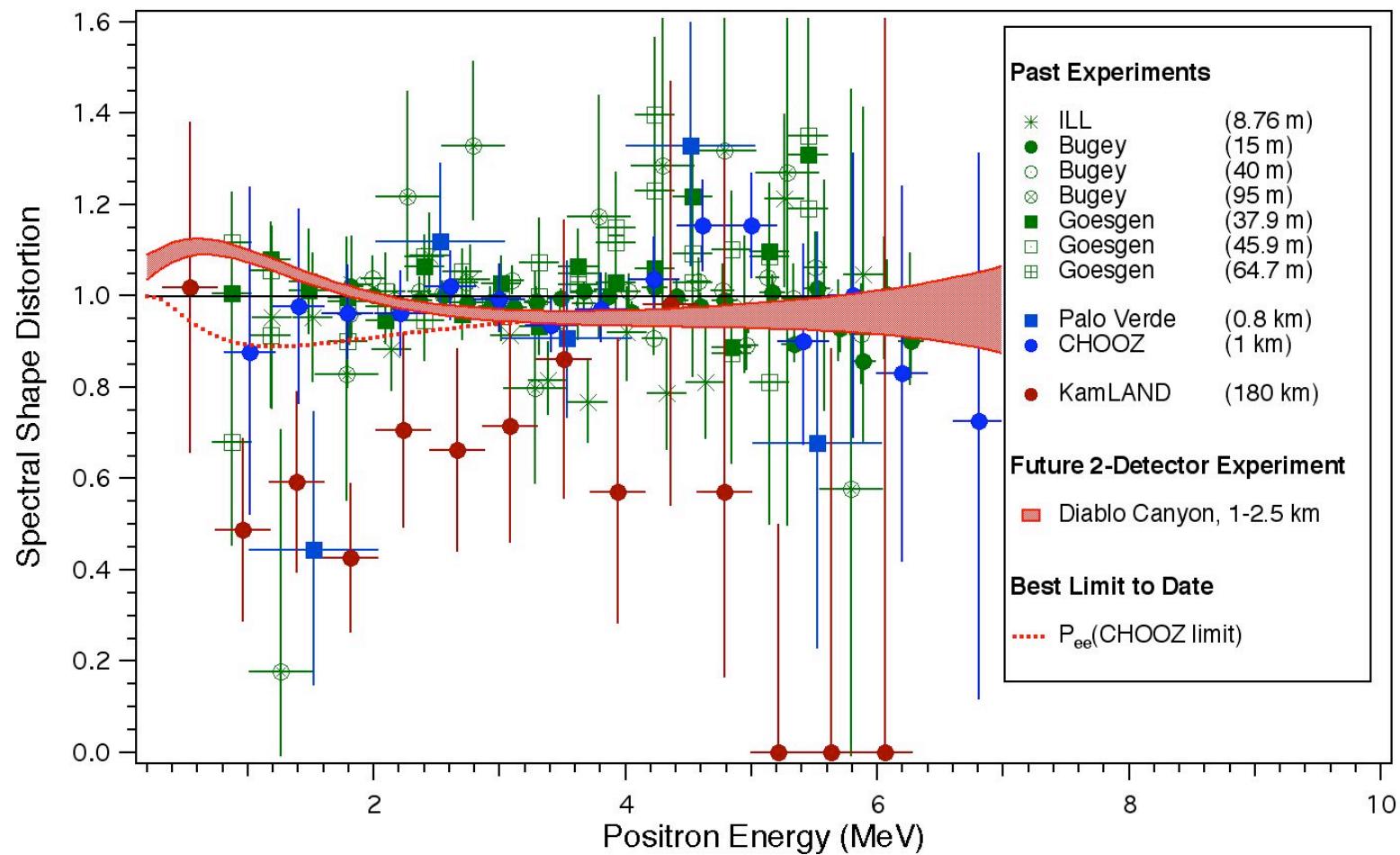
# Past and Present Reactor Neutrino Experiments

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# Future Diablo Canyon Experiment

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# Sensitivity and Complementarity of $\theta_{13}$ Experiments

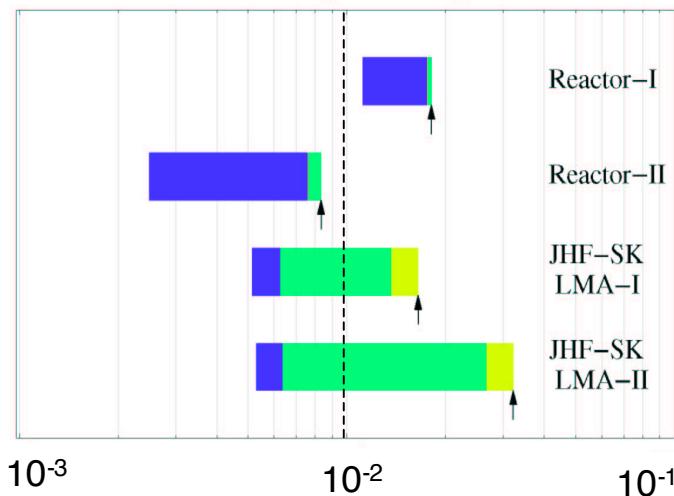
## Reactor Neutrino Measurement of $\theta_{13}$

- No matter effect
- Correlations are small, no degeneracies
- Insensitive to solar parameters  $\Delta m_{12}^2, m_{21}^2$

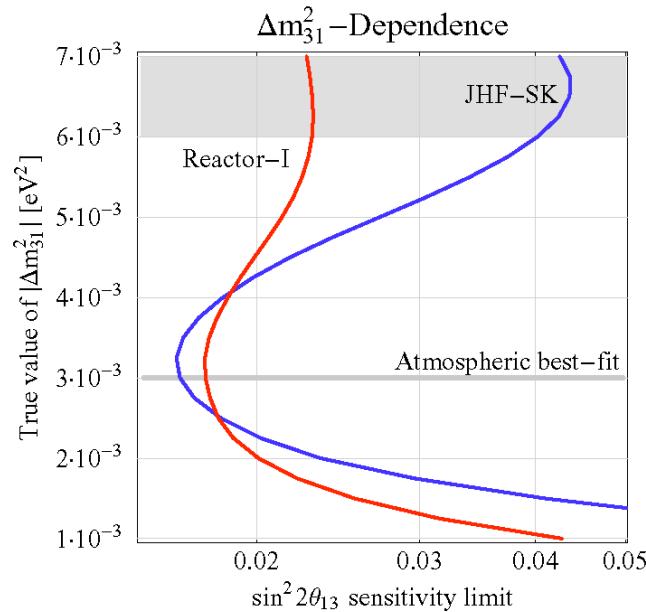
$\sin^2 2\theta_{13} < 0.01\text{--}0.02$  @ 90 C.L.

within reach of reactor  $\theta_{13}$  experiments

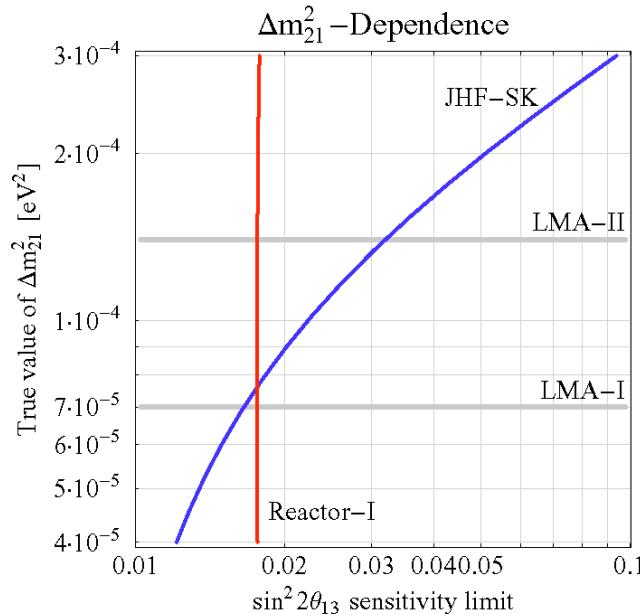
## Sensitivity to $\sin^2 2\theta_{13}$



Ref: Huber et al., hep-ph/0303232



Karsten



# Future Constraints on $\Delta_{13}$

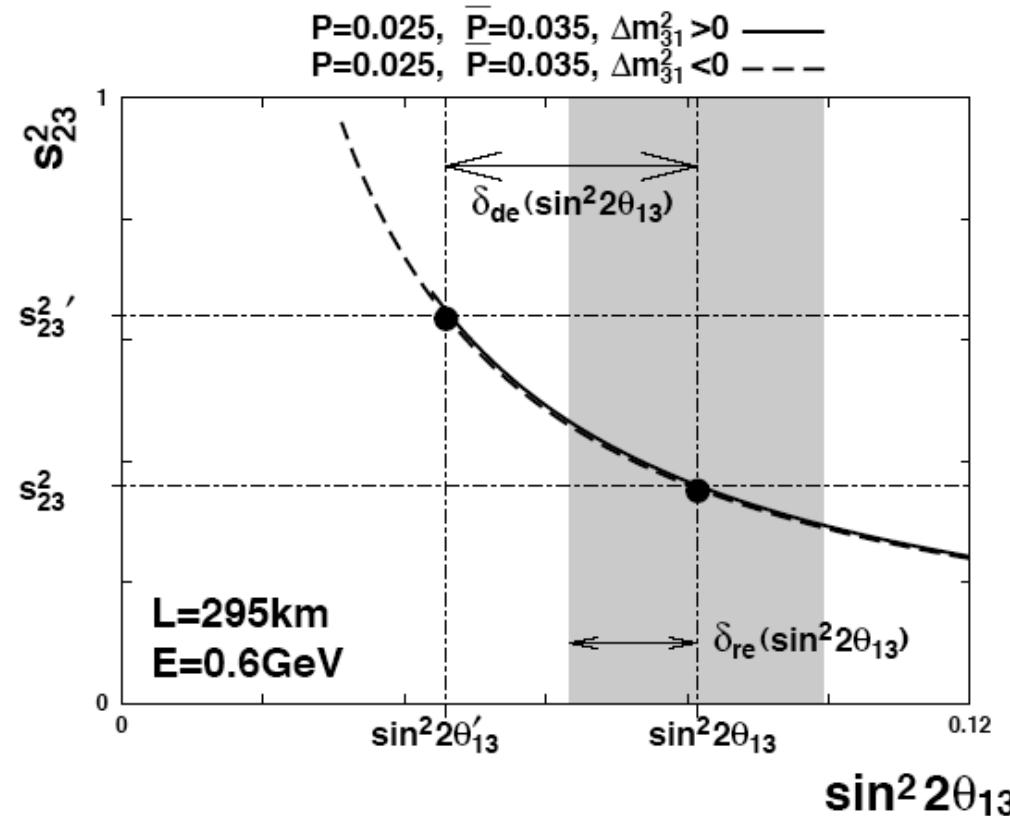
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<i>Experiment</i>	$\sin^2(2\Delta_{13})$	$\Delta_{13}$	<i>When?</i>
CHOOZ	< 0.11	< 10	
NUMI Off- Axis (5 yr)	< 0.006-0.015	< 2.2	2012
JPARC-nu (5 yr)	< 0.006-0.0015	< 2.3	2012
MINOS	< 0.06	< 7.1	2008
ICARUS (5 yr)	< 0.04	< 5.8	2011
OPERA (5 yr)	< 0.06	< 7.1	2011
KR2DET (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]
Penly/Cruas (France)	< 0.025	< 4.5	[2010]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]

Upper limits correspond to 90% C.L.

# Parameter Degeneracy

## Complementarity of reactor neutrino measurements of $\Delta_{13}$



observable effect of CP violation scales with  $\Delta_{13}$

# Summary: Reactor Measurement of $\theta_{13}$

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- Reactor neutrino oscillation experiment is **promising option** to measure  $\theta_{13}$ .
- Novel reactor oscillation experiment gives **clean measurement of  $\sin^2 2\theta_{13}$** , no degeneracies, no matter effects.

*2 or 3 detectors*

*variable baseline*

*largely independent of absolute reactor flux and systematics*

Moderate Scale (~\$M40)    Cost driven by tunnel excavation  
                                    Little R&D necessary (KamLAND, SNO, CHOOZ)  
                                    Construction time ~ 2-3 yrs  
                                    Start in 2007/2008?

- Negotiations with US power plants underway. Diablo Canyon is an attractive possibility.

**<http://theta13.lbl.gov/>**

